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State of the Sea Around Tropical Cyclones in the Western North Pacific Ocean

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ABSTRACT

The combined sea-height data for the year 1971 for the western North Pacific Ocean are examined to determine the sea-state characteristics around tropical storms and typhoons. The results show that the areal extent about the storms of the combined sea height in the 9–15 ft range is primarily a function of storm duration, intensity (maximum sustained wind) and size. Equations derived by linear regression techniques are presented for describing the state of the sea about tropical cyclones.

1. Introduction

One of the more difficult analyses the Navy forecaster is concerned with is the combined sea-height analysis,[1] especially when a tropical cyclone is present on his map. Most analysts agree that problems are caused by 1) the lack of data surrounding storms, 2) subjective observations, and 3) subjective analyses. An attempt is made in this paper to resolve part of the problem by establishing a more objective way to define the state of the sea about tropical cyclones. This will not only improve the product but also make it more consistent. These inconsistencies are evident if the combined sea-height analyses of separate meteorological/oceanographic centers are compared.

The differences dramatically emphasize the need for a more objective way to examine the sea-state analysis problem—to say nothing of the forecast problem, which is highly dependent on the initial analysis.

Ship captains are seriously concerned with sea states around tropical cyclones, since sea conditions affecting storm evasion or ship movement can cover a much larger area than the wind associated with the storm. A miscalculation concerning a building sea condition could lead to a destructive rendezvous with a tropical cyclone.

The purpose of this paper is to provide the operational forecaster with information which, in conjunction with conventional analysis and prediction techniques, should be a useful aid in both typhoon evasion and ship routing procedures. It is also intended to familiarize the ship captain with sea-state characteristics associated with tropical cyclones.

2. Data and method of analysis

In this study 21 tropical storms and typhoons which occurred in the months of July–November 1971 in the western North Pacific (excluding the South China Sea) were examined. Combined sea-height data were available for 173, 12 h analyses for these 21 tropical cyclones.[2] From each of the analyses, the distance out from the storm center of the 9, 12 and 15 ft isopleths of combined sea height were obtained (8-point compass values) for all stages of storm intensity. Values were radially averaged and the resulting average distances from the storm centers were compared with the meteorological parameters associated with the storms. The 8-point compass values relative to the direction of movement of the storm centers were also evaluated to determine the sea-state asymmetries present about the storms.

For purposes of this study, combined sea-height values for heights >15 ft were not examined because of the lack of data and observational and analysis problems. It was felt that conclusions could not be drawn for sea heights >15 ft,[3] but that sufficient data were available for meaningful conclusions in the 9–15 ft range.[4]

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[1] The combined sea height is defined as the square root of the sum of the squares of "significant" sea and swell height. Sea is wind waves and swell consists of wind-generated waves which have advanced into regions of weaker or calm winds. "Significant" will be defined here as the average height of the highest one-third of the waves observed over a specified time.

[2] Subjective combined sea-height analyses are produced operationally for the western North Pacific area by the U. S. Fleet Weather Central, Guam, and by Optimum Track Ship Routing, Fleet Numerical Weather Central, Monterey, Calif.

[3] Verploegh (1961) estimated the average observational error for a visual observation of wave height varies from 1 ft at 5 ft wave heights to 3 ft at 18 ft wave heights.

[4] In the average, for each of the 173 analyses examined, there were more than 20 ship observations available for analysis in this height range in the area around the tropical cyclones.
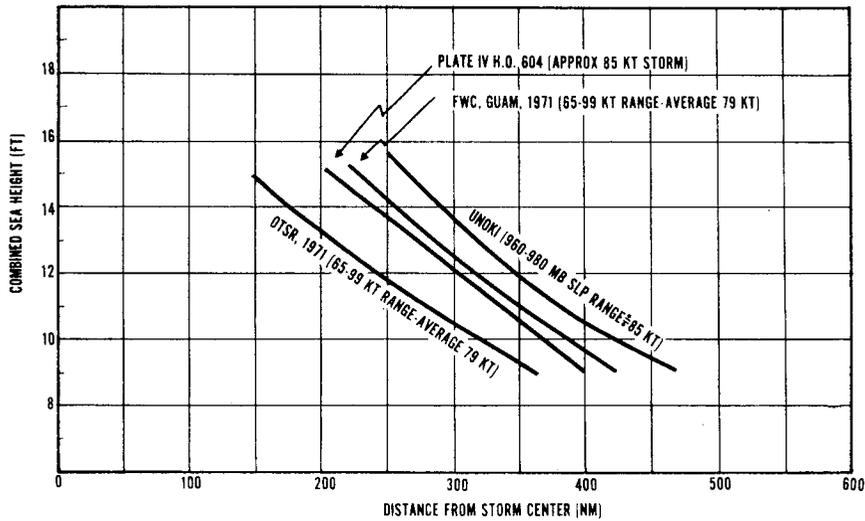
FIG. 1. Comparisons of the combined sea height around tropical cyclones
for a similar intensity category.

3. Discussion of results

Most of the research concerning the sea state near tropical cyclones has been observational in nature (Tannehill, 1936; Arakawa and Suda, 1953; Arakawa, 1954; Pore, 1957; Unoki, 1956, 1957a, b, c; Ijima, 1957). Numerical modeling of the sea states about tropical cyclones (Devillaz, 1967; Laevastu *et al.*, 1974) is rather new but the results are rapidly approaching those of models derived by empirical methods.

Although there have been many observational and theoretical studies on this topic, very little has been done to aid the analyst and forecaster. Unoki (1957c), after examining a number of typhoons to the east

of Japan, derived empirical formulas and diagrams to serve as a first guess for the wave heights and wave periods about tropical cyclones. The only input parameter required was storm intensity.[5]

The analyst also has available the relationships between the wave height and the surface wind, fetch length and wind duration (U. S. Naval Oceanographic Office, 1966). These relationships have been developed on the basis of theoretical considerations and empirical laws and are not specifically directed to the small scale of a tropical cyclone. However, they can be modified for a particular storm if certain assumptions

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[5] Unoki's results are biased somewhat toward the faster moving, higher latitude, recurved tropical cyclones to the east of Japan.
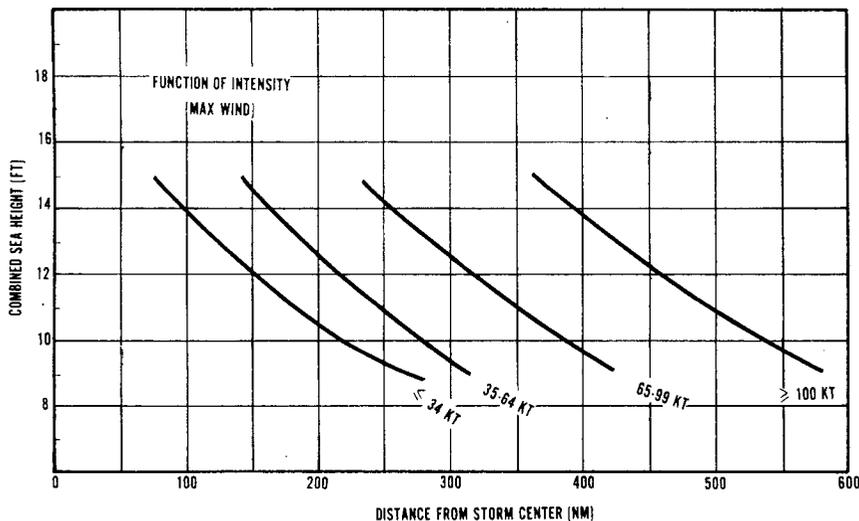

FIG. 2. The combined sea height (9–15 ft range) around 21 tropical storms and typhoons (based on 173 analyses for the year 1971) plotted against distance from storm center and given as a function of intensity.

TABLE 1. The mean distance and standard deviation from the storm center of the 9, 12 and 15 ft combined sea heights, as derived from the 173 analyses (21 tropical storms and typhoons) from FWC. The values are presented as a function of intensity category.

Intensity category (kt)	Combined sea height (ft)	Mean distance (n mi)	Standard deviation (n mi)	Number of analyses
⩽ 34	9	278	148	17
	12	157	125	17
	15	77	91	⸜17
35–64	9	317	170	61
	12	217	141	61
	15	143	123	61
65–99	9	421	210	60
	12	313	177	60
	15	237	145	60
⩾ 100	9	576	160	35
	12	454	137	35
	15	362	115	35

TABLE 3. The mean distance and standard deviation from the storm center of the 9, 12 and 15 ft combined sea heights derived from the 173 tropical cyclone analyses examined. Also presented is the standard error of estimate found by incorporating equations shown in Table 2.

Combined sea height (ft)	Mean distance from center (n mi)	Standard deviation (n mi)	Standard error of estimate (n mi)
9	415	185	113
12	299	161	93
15	217	141	77

are made concerning fetch length, wind duration and wind distribution.

It thus became apparent that there was a need for an objective way to describe the sea state about storms with input which would be readily available to the analyst, forecaster or even ship captain.

In order to compare the combined sea-height values of operationally produced analyses with those of other observational or empirical studies, a common intensity category was selected and compared. The range selected was the 65-99 kt category and comparative results can be seen in Fig. 1. The U. S. Fleet Weather Central (FWC), Guam, and Optimum Track Ship Routing (OTSR), Fleet Numerical Weather Central, Monterey, values are those derived from a homogeneous set of analyses for the same tropical storms

TABLE 2. Regression equations for describing the sea state around tropical cyclones in the 9–15 ft range of combined sea height.

$$R_9 = 60.72 + 0.24 \text{ Dur} + 0.03I + 0.55 \text{ Siz} - 0.19 \text{ H7R} \quad (1)$$
$$[N=173, \text{ multiple correlation coefficient} = 0.80]$$
$$R_{12} = 56.61 + 0.19 \text{ Dur} + 0.03I + 0.48 \text{ Siz} - 0.18 \text{ H7R} \quad (2)$$
$$[N=173, \text{ multiple correlation coefficient} = 0.82]$$
$$R_{15} = 44.21 + 0.16 \text{ Dur} + 0.03I + 0.42 \text{ Siz} - 0.14 \text{ H7R} \quad (3)$$
$$[N=173, \text{ multiple correlation coefficient} = 0.84]$$

Definition of Parameters Used

R_9 Average radius from the storm center to the combined sea-height isopleth of 9 ft, in degrees latitude.

R_{12} Average radius from the storm center to the combined sea height isopleth of 12 ft, in degrees latitude.

R_{15} Average radius from the storm center to the combined sea height isopleth of 15 ft, in degrees latitude.

Dur   Number of 12 h periods from the beginning of the life cycle of the storm (originating at issuance of first warning).*

I Storm intensity [maximum sustained wind (kt)].

Siz   Storm size (average radius to the outer closed surface isobar in degrees latitude).

H7R   Geopotential height of the 700-mb ridge (at ridge line) to the north of the storm in geopotential decameters.

* Experience during the 1971 season shows this point in the life cycle of the storms corresponds to a wind speed of about 35 kt.

and typhoons as were described previously. The H. O. 604 values have been derived from wave height and wind speed empirical relationships (U. S. Naval Oceanographic Office, 1966) incorporating a number of necessary assumptions because of the small scale of tropical cyclones. Unoki's values are based on his observational studies and have been converted from minimum sea-level pressure to maximum wind.[6]

Based on the comparisons shown in Fig. 1, it was concluded that the OTSR values were low and that the FWC analyses were realistic. The FWC analyses were therefore selected to form a basis for equations describing the sea states about tropical cyclones.

Tropical cyclone intensity (maximum sustained wind) and its relationship to sea state is an important parameter, but it was found that the length of time the storm existed and the size of the storm (circulation size) were also very important. Fig. 2 shows an example of how the combined sea height varies as a function of distance from the storm center for individual storm intensity categories.[7] The mean values presented here have been derived from the FWC combined sea-height analyses around the 21 tropical storms and typhoons discussed earlier. Note the large variation of the state of the sea as a function of storm intensity.

An average tropical storm (found in the range of 35-64 kt) could expect 12 ft seas (in the mean) 217 n mi from the storm center; while an intense typhoon (⩾ 100 kt) could expect 12 ft seas (in the mean) 454 n mi from the center. Table 1 shows the standard deviations about the mean, and the number of analyses contributing to the mean, for each of the sea-height values and for each intensity category. For example, intense typhoons (⩾ 100 kt) could expect 12 ft seas to

[6] Although there are many conversion schemes available to the Joint Typhoon Warning Center, Guam, they have found the relationship proposed by K. Takahashi of Japan to be the most accurate:

$$V_{max}(\text{kt}) = 13.4 [1010 - \text{Min SLP (mb)}]^{\frac{1}{2}}.$$

This relationship was therefore used to convert Unoki's values.

[7] It should be emphasized that these are mean values and they are radially averaged. The asymmetry about the storm center will be discussed later.
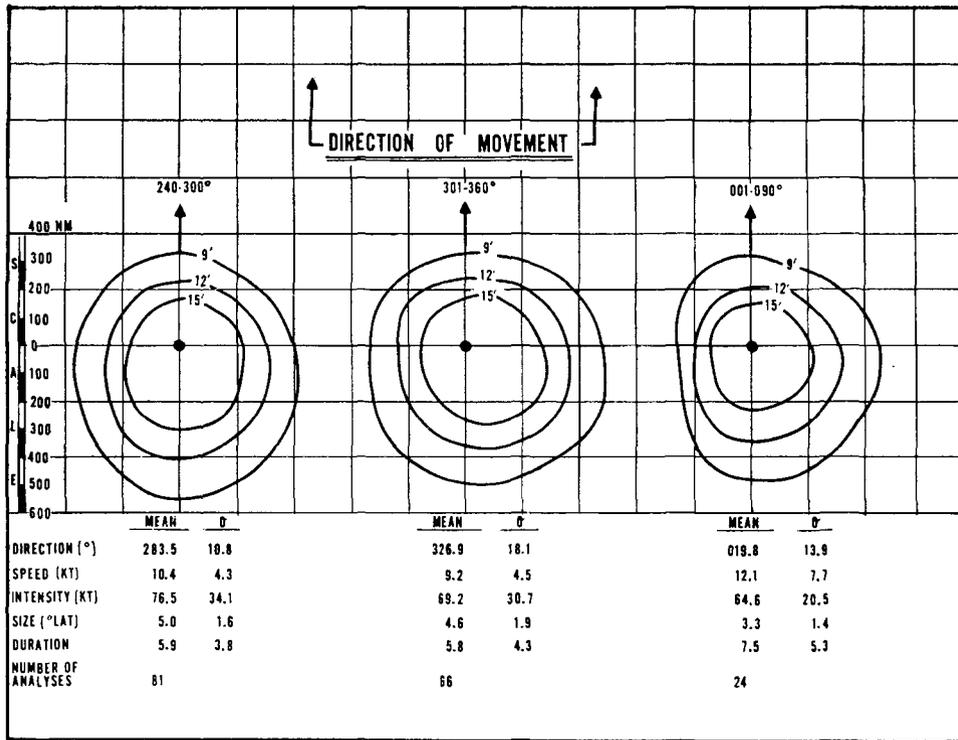
FIG. 3. The combined sea-height isopleths (9–15 ft) about tropical storms and typhoons given as a function of direction of movement. Means and standard deviations for the parameters associated with the storms are given for each movement category.
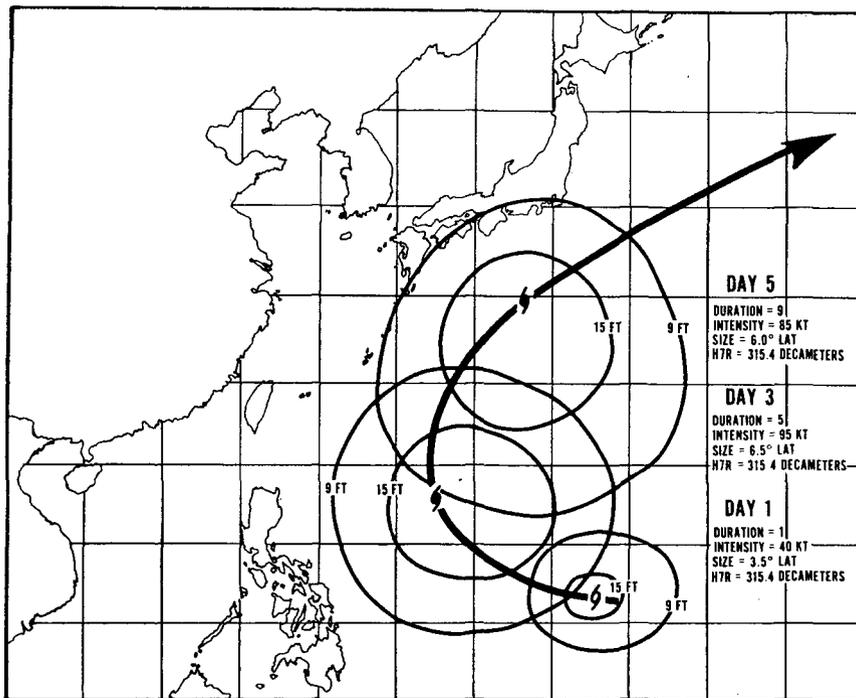

FIG. 4. Schematic example of the sea states about a recurving typhoon in the western North Pacific Ocean. Sea-height values (9 and 15 ft) have been obtained from the equations in Table 2, and modified by the asymmetry shown in Fig. 3.

fall in the range from 317 to 591 n mi from the center (mean value of 454 n mi) two-thirds of the time. Thus, it can be seen, the variation about the mean can be considerable.

Equations describing the sea states about tropical cyclones were developed using a stepwise regression computer program. The average radius to the height of the 9, 12 and 15 ft combined sea heights (R_9, R_{12}, R_{15}) of the FWC analyses were used as the dependent variables. The following 12 parameters were evaluated as possible independent variables:

1. Month
2. Storm duration—length of time storm has existed
3. Latitude
4. Longitude
5. Maximum wind
6. Speed of storm
7. Size of storm—average radius to outer closed surface isobar
8. Past 12 h latitudinal displacement of storm center
9. Past 12 h longitudinal displacement of storm center
10. Past 24 h change in maximum wind
11. Difference in degrees latitude of the 700 mb ridge line due north of storm to latitude of storm center position
12. Geopotential height of 700 mb ridge (at ridge line) due north of storm

The following criteria had to be met in order for equations for R_9, R_{12} and R_{15} to be accepted:

(i) The regression equations had to have a multiple correlation coefficient of at least 0.8 and also be significant at least at the 0.1% level.

(ii) The equations were limited to four independent variables. (It was felt that the use of more than four variables would be operationally difficult and not significantly increase the explained variance.)

Table 2 shows the resulting equations for describing the sea state about tropical cyclones. The variables given in the equations are presented in order of their importance in the regression analysis. It is interesting that the speed of the storm was not as important a consideration as storm duration, intensity, size, and the 700 mb ridge height value to the north of the storm. The storm duration turned out to be the most significant variable.

For each sea-height category, the standard error of estimate[8] of the mean distance from the storm center is markedly smaller than the standard devia-

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[8] Standard deviation of the differences between the observed values and the predicted values using the regression equations.

tion of the mean distance from the storm center (Table 3).

4. Some additional considerations

In order to determine the asymmetry of the isopleths of combined sea height about the storm center, the sea-height values (method described in Section 2) were examined relative to storm direction of movement. The results can be seen in Fig. 3, for three direction of movement categories—westerly, northwesterly and northeasterly. In general, it can be seen that areas of higher seas in the 9–15 ft range exist to the rear of the storm as well as toward the right semicircle relative to the direction of movement. The greatest asymmetry exists with storms after recurvature (storm heading 001°–090°). It is interesting that the geometric centers of the isopleths are consistently about 100 n mi toward the right and to the rear of the storms relative to direction of movement. (Note that the mean storm intensity for these categories varied from 64.6 to 76.5 kt.) This distance would tend to be smaller for storms of less than typhoon intensity and larger for more intense typhoons.

It should be pointed out that the conclusions derived from this study have been for one specific area, the western North Pacific Ocean to the east of the Philippines. It would be premature to say that these results apply to other tropical cyclone areas of the world. In fact, a cursory examination of South China Sea tropical cyclones indicates that the average radii of the 9–15 ft isopleths of combined sea height are approximately 15–20% smaller for similar intensity categories. The fact that tropical cyclones are markedly affected by the Philippines as they cross into the South China Sea (Brand and Blelloch, 1973) may account for part of the difference, but this has yet to be examined. The limited fetch length for a confined area such as the South China Sea is an additional factor.

The asymmetry considerations noted above, in conjunction with the statistical information presented previously, should aid the analyst or forecaster in describing the sea states about tropical cyclones using input parameters readily available to him. (An example is given in Fig. 4). Using information for the parameters as derived by conventional prediction techniques, he could also produce forecast sea-state conditions. This should be of value in typhoon evasion and ship routing procedures in the western North Pacific Ocean.

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